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RELIABILITY ANALYSIS OF THERMAL POWER GENERATING UNITS BASED ON WORKING HOURS

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Abstract

For any system reliability calculation, estimation plays a vital role and hence the analysis is to be diverted to calculate reliabilities of the units. To do this, we need to analyze failure rates or inter-failure time intervals or duration of the failure free operation of the units. This data is usually termed as Working Hours (successive failures). Working Hours implies that the gap between failure to failure which is directly linked with the reliability of the system. Hence in this paper, first we fit and test the suitability of the data using Exponential and Weibull distribution through chi-square Goodness of Fit (GoF) test. In the later part, reliabilities of different units are calculated using the same distributions. Conclusions are drawn based on the results obtained.

Key Words: Repair Hours, Failure Rate, Exponential Model, Weibull Model, Reliability, Working Hours.

1. Introduction

Thermal power generation being one of the important power sources among other power sources, now days exposed to lots of challenges. System complexity, poor design, expertise human resource capital, lack of maintenance, climatic conditions, scarcity of materials and so on are some of the causes of failure that are gaining more importance. Due to all these issues, generation of electricity has been suffering from long time. The facts and figures stated by Ministry of Power further tell the seriousness of the problem; among them, some are given below:

- Power sector is one of the fastest growing sectors in India, which essentially supports the economic growth. The power sector needs to grow at the rate of 12% to maintain the present GDP growth of 8%.
- Presently the energy deficit is about 8.3% and the power shortage during the peak period is about 12.5%.
- The total installed capacity of the power generating units is about 1,24,310 MW. Thermal power generating units contribute 66.4% of total installed capacity. The average plant load factor of the thermal power generating units is 74.8%.
  (Source: Ministry of power website – www.powermin.nic.in)

Thus, in the present scenario, apart from capacity escalation, there is an immense need to improve the performance of the individual thermal power generating units. The performance improvement of individual thermal power generating units will help in achieving increased power generation, reduction in power generation cost and thereby reducing the demand and improving the competitiveness of the Indian power industry.

A probabilistic analysis of the system under given operative conditions is helpful in understanding the behavior of the units of thermal power plant which further helps in statistical modeling to analyze failure in the system i.e. to optimize the system working. Therefore in order to correctly assess the problem and efficient functioning of the thermal units, it is very essential to correctly model and test it through probabilistic approach. Thus, the present paper investigates the suitability of Exponential and Weibull distributions through chi-square test of GoF regarding failures of thermal power unit data. Since higher availability of a power plant is depending upon higher reliability, the study is extended to reliability analysis to analyze the reliability of each unit of thermal power plant. For the present study, we have chosen Raichur Thermal Power Station (RTPS), Raichur, Karnataka to study thermal units. A unit represents the system consisting of stem generator, boiler furnace and stems drum, super heater, reheater, stem turbine, auxiliary systems, fuel preparation system etc involving in electricity production. There are seven such power generating units at RTPS. Working hours and Repair hours are collected from the seven units during the period 2004-2011.

2. Survey of Literature

Adhikary et al. [1] dealt a case of “RAM investigation of coal-fired thermal power plants: A case study”. The authors have investigated the reliability, availability and maintainability (RAM) characteristics of a 210 MW coal-fired thermal power plant (Unit-2) from a thermal power station in eastern region of India. Analyses of components/equipments have been tested through distribution, later GoF test have been performed through Kolmogorov–Smirnov Test. Critical mechanical subsystems with respect to failure frequency, reliability and maintainability are identified for taking necessary measures for enhancing availability of the power plant and the results are compared with Unit-1 of the same Power Station. The author concludes that RAM analysis is very much effective in finding critical subsystems and deciding their preventive maintenance program for improving availability of the power plant as well as the power supply.

Fernando Jesus Guevara Carazas and Gilberto Francisco Martha de Souza [2] consider the case of “Availability Analysis of Gas Turbines Used in Power Plants”. In the paper, the reliability analysis is performed for two gas turbines installed in the power plant. The reliability analysis is based on the time to failure data analysis. The method allows one to carry out system reliability, maintainability and availability analyses. Reliability tests have been performed through Exponential, Weibull and Lognormal Distributions. Both gas turbines’ reliability and availability estimates were considered as preliminary. The improvement of ‘time to failure’ and ‘time to repair’ databases during future operational years (with the addition of more failure and repair data) allows more reliable estimates of the turbines reliability and availability. Nevertheless these estimates can be used to check design and maintenance procedures in order to adopt them to the gas turbine local operational condition that may be different from the average condition considered in the equipment design. The author concludes that, these estimates can also be used for benchmarking in order to compare the performance of the same gas turbine model operating in different sites.

Krishna Reddy [6] dealt a case of "Modeling the Causes of Production Downtimes: An Empirical Study of a Thermal Power Generating Unit". An attempt is made to find which distribution is best fitted for working time between successive failures (working hours) and downtime (repair hours). Exponential and Weibull distributions are commonly assumed model of failure time and repair time. Chi-square test is used to test the GoF.

Romeu [8] discussed GoF test using various distributions in "The Chi-Square: a Large Sample Goodness of Fit Test". In the study, the author has developed a model to fit the data using Normal Distribution, Exponential Distribution and Weibull Distribution. Then Chi-Square test was applied to know the underlying distribution supports the data or not. The author has taken several examples namely Normal, Lognormal, Exponential and Weibull distributions and showed how the GoF can be dealt via Chi-Square test.

Hungund and Patil [4] analyzed and compared critically using repair hours of different power units using Exponential distribution. It has been observed that the distribution did not give a good fit to the repair hour data for all the power generating units. Hence it was concluded that the procedure for fitting the data need to be further developed.

3. Objectives

The objectives of the present study are:

- To fit the Exponential and Weibull distribution for working hours of seven power units of a thermal power plant.
- To test the suitability of Exponential and Weibull through the chi-square test of GoF.
- To test the reliability of seven power units of a thermal power plant.
- To compare the Exponential and Weibull reliabilities.

4. Goodness of Fit Test

As it was stated that the failures of thermal units are due to various reasons. In order to identify the best suitable analysis, the collected data has been split into two categories viz., Category-I and Category-II. Category-I is based on minor working hours and category-II is based on major working hours.

4.1 Fitting of Exponential Distribution

Exponential distribution is commonly assumed model for time to failure data. Here an effort is made to fit the data using Exponential distribution for failures (working hours).

4.1.1 Probability Density Function (PDF)

The PDF of an Exponential distribution is

$$f(x;\lambda) = \lambda e^{-\lambda x}, x \geq 0 \tag{4.1}$$

where λ is the parameter.

The parameters are usually unknown and are to be estimated from the data. It is also necessary to check whether the distribution of observed data fits into one of the known theoretical distributions or not, so that the distribution can be better understood if necessary.

4.1.2 Cumulative Distribution Function (CDF)

The CDF of Exponential distribution is given by:

$$F(x;\lambda)=1-e^{-\lambda x}, x\geq 0 \qquad (4.2)$$

4.1.3. Testing of Hypothesis

The hypothesis of the problem is given by:

H_0: Exponential Distribution is good fit for the data

Ha: Exponential Distribution is not a good fit for the data.

Using the procedure developed in the paper Hungund and Patil [4], we obtain the following results for fitting an Exponential distribution for whole and categorical data on working hours for seven units which are summarized in tables 1 and 2 with chi-square value to test its GoF.

Units	n	k	Mean	Lamda	Chi-Square	DF
Unit 1	74	10	26.55	0.038	29.85	6**
Unit 2	94	11	13.4	0.4	182.29	7**
Unit 3	56	7	38.78	0.026	11.83	3**
Unit 4	59	9	40.33	0.025	16.74	5**
Unit 5	52	8	44.05	0.023	7.45	5
Unit 6	46	6	51.7	0.019	1.81	3
Unit 7	79	8	27.51	0.036	13.14	5**

Table 1: Summary of Exponential distribution working hours for whole data

Units	Category	n	k	Mean	Lamda	Chi Square	DF
Unit 1	Category-I	40	5	5.15	0.194	9.86	3*
	Category-II	34	5	51.72	0.019	5.76	1*
Unit 2	Category-I	50	6	1.46	0.685	10.55	3*
	Category-II	44	6	26.97	0.037	5.56	4
Unit 3	Category-I	28	4	5.36	0.187	3.1	2
	Category-II	28	4	72.21	0.014	6	1*
Unit 4	Category-I	30	5	5.95	0.168	1.54	2
	Category-II	29	4	75.89	0.013	4.17	2
Unit 5	Category-I	26	4	8.78	0.114	0.37	1
	Category-II	26	4	79.31	0.013	1.18	2
Unit 6	Category-I	24	3	11.05	0.09	3.03	1
	Category-II	22	3	96.04	0.01	2.15	1
Unit 7	Category-I	40	4	4.91	0.204	0.75	2
	Category-II	39	4	50.64	0.02	4.56	2

Table 2: Summary of Exponential distribution working hours data for categorical data.

*: Rejected at 5%, **: Rejected at 5% & 1%.

The analysis of the results obtained in Tables 1 & 2 estimating the statistical parameter for working hours of seven units imply that the working time data are fitted with Exponential and Weibull distributions. From Table 1, it is inferred that the Exponential distribution is not a good fit to the data on working hours, except for unit 5 and unit 6 at 5% level of significance and unit 5, 6, 7 at 1% level of significance. Hence we split the data into two categories. From table 2 it can be observed that the Exponential distribution gave a good fit for categorical data of working hours for all the units at 1% level of significance. At 5%, except unit-1 and category-2 of unit-3, the data of all other units show Exponential distribution gave a good fit for working hours. We claim that splitting of data into two categories minor repair hours and major repair hours helps to analyze failure in the system i.e. to optimize the working hours in the system.

4.2 Fitting of Weibull Distribution

Romeu [9] discusses some empirical and practical methods for checking and verifying the statistical assumptions of the Weibull distribution in the paper "Empirical Assessment of Weibull Distribution". The author has elaborated the statistical assumptions of Weibull distribution by taking several numerical and graphical examples. Two approaches were used to assess the distribution assumptions. One is by implementing numerically convoluted, theoretical GoF and other practical procedures that are based on intuition and graphical distribution properties. In the following sections an attempt is made to show that the data assumes Weibull distribution by verifying the statistical assumptions of Weibull distribution numerically and graphically.

4.2.1 The PDF and CDF of Weibull Distribution

Consider the PDF and CDF of Weibull distribution

$$f(x) = \frac{\beta}{\alpha^{\beta}} x^{\beta-1} \exp\left\{-\left(\frac{x}{\alpha}\right)^{\beta}\right\} \tag{4.3}$$

$$F(x) = 1 - \exp\left\{-\left(\frac{x}{\alpha}\right)^{\beta}\right\} \tag{4.4}$$

4.2.2 Estimation of Weibull Parameters

Taking the logarithms of the distribution function F(x) (eqn. 4.4) and doing some algebra, we obtain:

$$Log\left\{Log\left(\frac{1}{1-F(x)}\right)\right\} = -\beta Log(\alpha) + \beta Log(x) \tag{4.5}$$

When the distribution of the failure is really Weibull, the above equation is that of a line. Now assume that an estimation of F(x) can be obtained and denote it Px. We then can substitute Px in lieu of F(x) in the equation and solve for x. To estimate Px for any data point x, i.e. the median rank by defining:

$$F(x) \cong Px = \frac{Rank(x) - 0.3}{n + 0.4} \tag{4.6}$$

Where Rank(x) is the rank of x, in the sorted sample. Using such Px values, we can plot the regression line on Log(Log(1/(1 – Px))) call it as Y against $Log_e(X)$ call it as X which is shown in the figure-1.

The collected data (Table 3) has been used to develop a model to fit the data of power units and tested good fit to the working hours for all seven units i.e. Unit-1 to Unit-7.

0.14	0.15	0.29	0.57	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.15	1.50
2.00	2.00	2.00	3.00	3.00	3.08	4.00
4.00	4.00	4.00	4.07	5.00	6.00	8.00
10.00	10.00	10.00	10.00	10.00	10.05	12.00
12	13.00	13.00	14.81	16.00	17.00	17.00
18.87	19.00	20.38	20.40	21.00	23.00	23.00
24.00	25.00	26.00	27.90	27.93	30.14	30.95
31.00	32.00	45.00	45.71	46.97	46.97	48.31
49.81	68.26	69.32	72.00	76.00	80.00	85.89
109.00	119.45	162.44	198.91			

Table 3: Working Hours of Unit 1

We obtain the intercept and slope of regression equation for the data X and Y using Microsoft Excel function '=intercept(Y,X)' and '=slope(Y,X)' respectively. Thus we have intercept=-1.9118 and slope (β)=0.6385. The characteristics life (α) of Weibull can be obtained computing

$$CharcteristicLife(\alpha) = Exp\left[-\left(\frac{Intercept}{Slope}\right)\right] = Exp\left[-\left(\frac{-1.9118}{0.6385}\right)\right] = 19.9772$$

Then the estimated regression equation will be $Y = -\beta Log(\alpha) + \beta x$.
The following table summarizes the regression results.

	Intercept - β*Log(α)	Slope (β)	CharLf (α)	Correlation (r)	Coeff of Determination (r^2)
Value	-1.9118	0.6385	19.9772	0.9951	0.9901

Table 4: Summary of Regression equation.

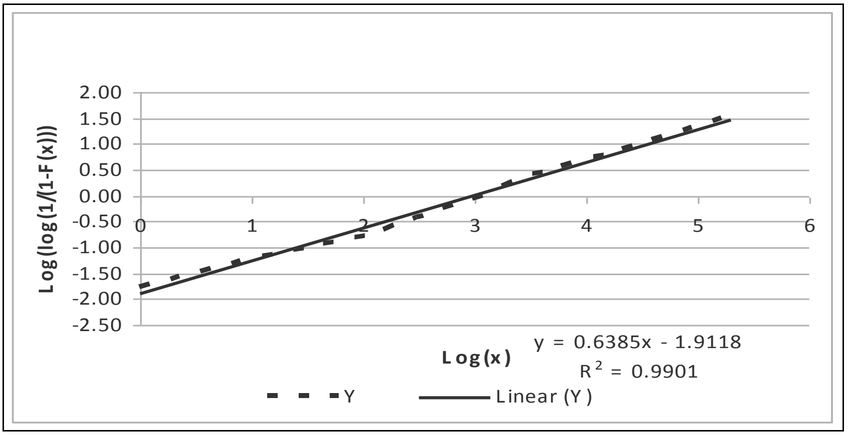

Figure 1: Comparison of actual data with fitted Weibull function of Unit-1.

From the figure-1 it is evident that the data is Weibull, since the plot of the transformed data is linear with slope β and intercept -βlog(α).

4.2.3 Testing of Hypothesis

The parameter estimation allows us to define the composite distribution hypothesis

H_0: The distribution of the population originating the data set is Weibull.

H_a: The distribution of the population originating the data set is not Weibull.

The above hypothesis is tested via the Chi-Square GoF test. For endpoints we now select 1.00, 3.00, 8.00, 12.00, 17.00, 23.00, 31.00, 48.00, 85.00 and 200.00 which in turn define subintervals. We also obtain the cumulative and individual cell probability values. For the first point, 1.0:

$$P_{\alpha=18.5714,\beta=0.6111}(1.0) = 1 - \exp\left\{-\left(\frac{Xi}{\alpha}\right)^{\beta}\right\} = 1 - \exp\left\{-\left(\frac{1.0}{19.9772}\right)^{0.6385}\right\} = 0.14$$

The resulting values are shown in the following table 5.

X	CumProb	CellProb	Expected	Observed	Chi-Square
1	0.14	0.14	10.17	12	0.33
3	0.26	0.12	8.91	8	0.09
8	0.43	0.17	12.55	8	1.65
12	0.51	0.09	6.44	8	0.38
17	0.59	0.08	5.92	6	0.00
23	0.67	0.07	5.25	7	0.59
31	0.73	0.07	5.09	8	1.67
48	0.83	0.09	6.83	6	0.1
85	0.92	0.09	6.91	6	0.12
200	1	0.08	5.95	5	0.15
Total			74	74	5.08

Table 5: Intermediate Values for the Weibull distribution GoF test.

Since we have estimated both α and β the resulting chi-square has degrees of freedom (df) =k-2-1=10-2-1=7. Here the chi-square statistic value (5.08) is not larger than the chi-square table value 14.03 for 7 df and α =0.05. Therefore we accept H_0 and conclude that the Weibull distribution is good fit to the data.

The procedure explained above to obtain GoF is for the Unit-1. Similar procedure can be applied to other units also. Results obtained for other units along with Unit-1 are given in Table 6 with their chi-square values to test the GoF.

Units	**n**	**k**	**Mean**	**Chi-Square**	**DF**
Unit 1	74	10	26.55	5.08	7
Unit 2	94	11	13.4	4.32	9
Unit 3	56	7	38.78	4.10	3
Unit 4	59	9	40.33	4.20	5
Unit 5	52	8	44.05	7.45	4
Unit 6	46	6	51.7	3.84	3
Unit 7	79	8	27.51	1.22	5

Table 6: Intermediate Values for the Weibull distribution GoF test.

It is interesting to note that the collected data on working hours need not be split into categories in case of Weibull distribution (Table 6). The analysis of the results obtained in Table 6 infer that the model gave a good fit to working hours for the entire unit both at 1% and 5% level of significance for the period of seven years.

5. Reliability Analysis

Reliability can be defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions. Implied in this definition is a clear-cut criterion for failure, from which one may judge at what point the system is no longer functioning properly. For the thermal power units the failure criterion is any component failure that causes incapacity of generating the nominal power output. The reliability analysis is performed for each of the thermal units in the power plant. The reliability analysis is based on the time to failure data analysis. To better understand the behavior of lifetime distributions, reliabilities of Exponential and Weibull analysis is performed in the following sections.

5.1 Reliability of Exponential Distribution

The Exponential distribution is one of the most widely used in reliability problems (particular case of a Weibull distribution with the shape parameter β = 1). The very reason behind popularity of this distribution can be attributed primarily to the fact that it is be used to model the time to failure of components and systems with constant failure rate, a situation that is often realistic. The reliability function is given below:

$$R(t) = e^{-\lambda t} \qquad (5.1)$$

The mean time to failure of the Exponential function is simply the inverse of the failure rate λ.

$$MTTF = \frac{1}{\lambda} \tag{5.2}$$

5.2 Reliability of Weibull distribution

The two-parameter Weibull distribution is used to model failures is represented by the following equation:

$$R(t) = \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right)$$

Where R(t) reliability at time t, t time period [h], β is Weibull distribution shape parameter and α is Weibull distribution characteristic life [h].

5.3 Reliability analysis of Exponential and Weibull distribution

The Weibull distribution parameters are estimated through the use of regression line that fit the distribution to the 'time to failure' data. The following table shows the Weibull parameters for all the units.

	Unit1	Unit2	Unit3	Unit4	Unit5	Unit6	Unit7
Mean	26.56	13.4	38.78	40.33	44.05	51.7	27.51
Intercept -βLog(α)	-1.91182	-1.05555	-2.11772	-2.32664	-3.05913	-2.63672	-2.27999
Slope (β)	0.638477	0.511687	0.626185	0.679697	0.835805	0.695358	0.731548
Alpha (α)	19.97222	7.868664	29.42774	30.66288	38.86505	44.34036	22.57102

Table 7: Summary of regression estimators for all the units.

Depending upon the values of the shape parameter (β), Weibull failure rate increases (β>1), decreases (β<1) or remains constant (β=1). Table 7 infers that all the units have reliability distribution with shape parameter less than 1. When 0<β<1, the distribution has decreasing failure rate. The reliability distribution for Exponential and Weibull distribution curve for all the units are presented in table 8 as well as figure-2. The points presented in the graph represent the median rank plotting reliability estimate for each of the time to failure data, arranged in increasing order. Those points are used to verify the adherence of the reliability distribution to the failure data.

Time 't'	Unit1		Unit2		Unit3		Unit4		Unit5		Unit6		Unit7	
	Expn	Weibull	Expn	Weibull	Expn	Weibull	Expn	Weibull	Expn	Weibull	Expn	Weibull	Expn	Weibull
5	0.83	0.71	0.69	0.55	0.88	0.76	0.88	0.79	0.89	0.85	0.91	0.82	0.83	0.75
10	0.69	0.59	0.47	0.42	0.77	0.65	0.78	0.68	0.80	0.75	0.82	0.73	0.70	0.62
15	0.57	0.50	0.33	0.35	0.68	0.58	0.69	0.60	0.71	0.67	0.75	0.66	0.58	0.53
20	0.47	0.43	0.22	0.29	0.60	0.52	0.61	0.54	0.64	0.60	0.68	0.60	0.48	0.45
25	0.39	0.38	0.15	0.25	0.52	0.47	0.54	0.49	0.57	0.54	0.62	0.55	0.40	0.39
50	0.15	0.22	0.02	0.14	0.28	0.31	0.29	0.31	0.32	0.33	0.38	0.38	0.16	0.21
100	0.02	0.10	0.00	0.06	0.08	0.16	0.08	0.16	0.10	0.14	0.14	0.21	0.03	0.08
150	0.00	0.05	0.00	0.03	0.02	0.10	0.02	0.09	0.03	0.06	0.05	0.12	0.00	0.03
200	0.00	0.03	0.00	0.02	0.01	0.06	0.01	0.05	0.01	0.03	0.02	0.08	0.00	0.01
300	0.00	0.01	0.00	0.01	0.00	0.03	0.00	0.02	0.00	0.01	0.00	0.03	0.00	0.00

Table 8: Reliability of the seven units of Thermal Power Plant at different time units 't'.

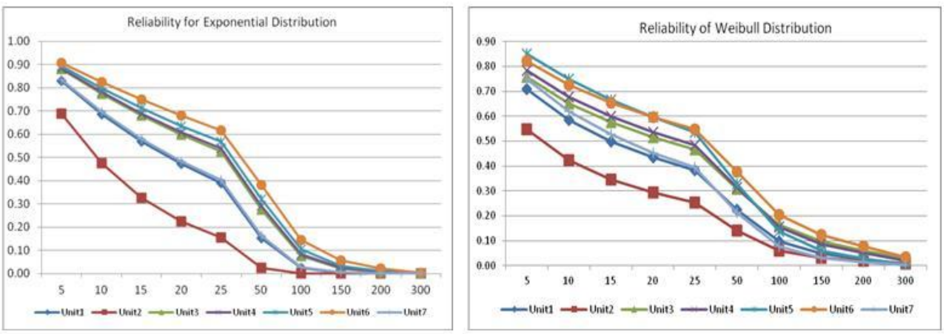

Figure-2: Graphs of the reliability of seven units at different time units t.

From Table 8, it is evident that Unit-6 in Exponential and Unit-5 in Weibull distribution shows higher reliability. This indicates that Unit-5 and Unit-6 are getting close to the period of random failures characterized by the shape parameter equal to 1. Whereas Unit-2 is showing lesser reliability in both the distribution when compared with other units which indicates necessary measure has to be taken for improvement. From figure-2 in the Weibull plot, though Unit-6 is showing lesser reliability initially compared to unit-5, but after 25th hours, Unit-6 starts showing good reliability than Unit-5. This concludes that unit-6 is best performing unit among the other six units. Also note that reliability of power units after 100 hours, Exponential reliability is below 0.10 mark, whereas its counterpart i.e. Weibull, still having better reliabilities. Even if we carefully observe, till 50^{th} hour, both reliabilities are more or less same. After that Exponential reliabilities start deviating (decreasing) with Weibull reliabilities, and it continues to be so for subsequent hours. The very reason we believe that Weibull distribution found good fit to the data for whole data.

6. Conclusion

The reliability analysis of thermal power generating units based on working hours have been tested through Exponential and Weibull distributions. Later GoF have been performed through chi-square test. The GoF test reveals that Weibull distribution is the most reliable distribution for fitting working hour data. Reliabilities are identified for taking necessary measures enhancing availability of the power plant.

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References

1. Adhikary D.D., Bose, G.K., Chattopadhyay, S.D., Bose, D. and Mitrad, S. (2012). RAM investigation of coal-fired thermal power plants: A case study, The International Journal of Industrial Engineering Computations, Volume 3, p. 423-434.
2. Fernando Jesus Guevara Carazas and Gilberto Francisco Martha de Souza (2009), Availability Analysis of Gas Turbines Used in Power Plants, Int. J. of Thermodynamics, Vol. 12 (No. 1), p. 28-37.
3. Freeman J. M. (1996). Analysing equipment failure rates, International Journal of Quality & Reliability Management, Vol. 13(4), p. 39- 49.
4. Hungund CPS and Shrikant Patil (2013). Analysis of Production Downtimes in Thermal Power Plant using Exponential Failure Model – A Case Study, Bulletin for Pure and Applied Sciences, International Journal for Statistics and Mathematics, Volume 32E, Issue (1) 2013, p. 113-120.
5. Kohichi Nakamura (1981). Reliability analysis of thermal power units based on the annual operating results Published online, Electrical Engineering in Japan, Volume 101(4), p. 78-87.
6. Krishna Reddy, B. (2008). Modeling the causes of Production downtimes: An empirical study of a Thermal Power Generating Unit, The ICFAI Journal of Operations Management, The Icfai University Press, Hyderabad May 2008, pp. 33-40.
7. Nair.P. and Vasakarla Jayavani (2006). Manual on Best Practices in Indian Thermal Power Generating Units, The IUP Journal of Infrastructure, The Icfai University Press, December 2006, Hyderabad.
8. Romeu, J.L. (2004). The Chi-Square: A Large Sample Goodness of Fit Test, RAC START, Volume 10 (4). Publication of Reliability Analysis Center.
9. Romeu, J.L. (2003). Empirical Assessment of Weibull Distribution, RAC START, Volume 10 (4), Publication of Reliability Analysis Center.